Impact of Air-Sea Interaction Research on Larger-Scale Geophysical Flows

Michael L. Banner
School of Mathematics, The University of New South Wales, Sydney 2052, Australia
phone: (+61-2) 9385-7072 fax: (+61-2) 9385-7123 email: m.banner@unsw.edu.au

Lance M. Leslie
School of Mathematics, The University of New South Wales, Sydney 2052, Australia
phone: (+61-2) 9385-7071 fax: (+61-2) 9385-7123 email: l.leslie@unsw.edu.au

Award #: N00014-00-1-0288
http://www.cemap.unsw.edu.au/wave

LONG-TERM GOALS

The long-term goals are to contribute improvements to current physical understanding and modelling of interfacial processes fundamental to air-sea interaction fluxes, particularly those involving wave breaking and associated processes of spray and spume production. Closely allied is the complementary goal of utilizing these advances to improve the reliability of operational sea state and ocean weather forecasting models, particularly for severe sea states.

OBJECTIVES

There is a growing active research community focus on *coupled* atmosphere-ocean models from synoptic weather systems and meso-scale ocean eddies, to basin scales, with a strong demand for optimal surface flux parameterizations. This need is also very strongly reflected within the operational modeling community. While not yet abundant, convincing evidence is building for significant forecast sensitivity to sea surface boundary conditions for both atmospheric and sea state variables, particularly in synoptic severe marine weather predictions. Examples are given in the recent work of Janssen (2000) and Buckley and Leslie (2000), with McWilliams and Restrepo (1999) highlighting the global impact on planetary scale ocean circulation of small-scale air-sea interaction (ASI) processes.
This project seeks to improve the reliability of coupled severe sea state/marine weather forecasting models. Our emphasis is to fill knowledge gaps in air-sea interfacial processes, with a particular focus on refining and incorporating the role of wave breaking and sea spray by developing more realistic parameterizations for breaking occurrence, strength and sea spray/spume source strength functions for implementation in a coupled COAMPS/WaveWatch III model for operational sea state forecasting.

APPROACH

This project began in FY00 with an initial study (MLB) involving interactions with researchers at key international air-sea interaction/larger-scale oceanographic/meteorological research centers. The major aim was to explore knowledge gaps and establish collaborative research on key air-sea interaction problems that impact on this area. Issues identified included Stokes' drift wave transport, Langmuir circulations, misaligned wind and wave fields, departures from Monin-Obhukov similarity structure, near-surface flow separation (especially over breaking waves), contributions to air-sea fluxes from

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2001**	2. REPORT TYPE	3. DATES COVERED **00-00-2001 to 00-00-2001**

4. TITLE AND SUBTITLE **Impact of Air-Sea Interaction Research on Larger-Scale Geophysical Flows**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **School of Mathematics,,The University of New South Wales,,Sydney 2052, Australia, ,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The long-term goals are to contribute improvements to current physical understanding and modelling of interfacial processes fundamental to air-sea interaction fluxes, particularly those involving wave breaking and associated processes of spray and spume production. Closely allied is the complementary goal of utilizing these advances to improve the reliability of operational sea state and ocean weather forecasting models, particularly for severe sea states.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

wave-correlated winds and currents including the effects of wave breaking on near-surface flow structures and fluxes, and mesoscale inhomogeneity and non-stationarity.

Arising from this initial study, a research focus emerged that identified the strength and distribution of wave breaking events, together with its associated processes, as fundamental to an improved understanding of ASI dynamics and energetics. This led to an intensive collaboration with D. Farmer and J. Gemmrich (IOS, Canada) on an extended analysis of their existing datasets. This collaboration has determined a robust threshold behavior based on a spectral measure of wave steepness that provides a universal parametrization for storm sea wave breaking probability in frequency bands above the wind sea spectral peak. This result is of primary importance in parameterizing wave breaking in spectral models and promises to underpin new source term formulations for the wave energy dissipation rate and spray/spume production.

In FY01, this project transitioned to a specific project within in the CBLAST hurricane modeling effort (MLB/LL) entitled 'Wave Breaking Influence in a Coupled Model of the Atmosphere-Ocean Wave Boundary Layers under Very High Wind Conditions'. The thrust of our effort within CBLAST is the development of new parameterizations of wave breaking physics in coupled air-sea interaction models for severe sea state conditions. Russel Morison was appointed as Senior Project Scientist (Jan. 2001).

WORK COMPLETED

During FY01, collaborative research with D. Farmer and J. Gemmrich (IOS, Canada) continued on parameterizing wave breaking probability in the wave spectrum, based on an extended analysis of their unique data set collected during storm events in the N. Pacific. This collaboration, initiated in FY00, has provides a robust new parameterization for breaking wave probability as discussed under 'Results'. The energy dissipation rate source term (S_{ds}) in spectral wind wave models is central to reliable sea state prediction of sea state and allied quantities of interest relating to wave breaking phenomena. The results quoted in the previous paragraph validate a new saturation-based threshold form for S_{ds} that provides greater flexibility and improved performance in fetch-limited wind wave evolution modeling (Alves and Banner, 2001) and underpins our CBLAST modelling effort.

Further joint research on refining sea spray/spume parameterization was initiated as a result of discussions at the inaugural CBLAST PI meeting in Washington (January 2001) with C. Fairall (NOAA, Boulder, Co) and E. Andreas (USACRREL, Hanover, NH). This collaboration is aimed at developing a new model for spume droplet production based on sea state properties (particularly wave breaking) rather than on wind speed.

Allied effort has focused on the acquisition and installation of the COAMPS version 3 and WaveWatch III version 1.18 models for atmospheric and sea state prediction. A significant effort has gone into understanding and porting the COAMPS code to our system, including the MPI (message passing interface). Both of these models have been successfully installed on our parallel computing system and we are now initiating coupling of these two models.

RESULTS

(i) *parameterizing wave breaking onset*

Sea state dependence of air-sea fluxes has been a strong focus of recent air-sea interaction research, with the role of wave breaking receiving increasing attention. Yet, basic aspects such as breaking probability and which environmental variables control it are poorly understood.

The collaboration with D. Farmer and J. Gemmrich (IOS) involved further analysis of their open ocean breaking wave dataset (GF99) for wave frequencies both at and above the spectral peak frequency. Breakers were detected by an air void fraction sensor mounted on a floating sub-surface raft, which also carried a device to detect the wave elevation or acceleration. The data was collected for a wide range of storm sea state conditions. The GF99 dataset was re-analysed using mean spectral steepness of the wave field as the primary correlation variable rather than the traditional parameters based on wind forcing strength.

The wave breaking results for the dominant wind sea agreed with the threshold behavior reported in Banner et al. (2000), according to which negligible breaking occurs below a threshold mean steepness, with a rapid increase of breaking probability above that threshold. To avoid bandwidth choice issues in describing higher frequency wave breaking, spectral saturation was introduced as an appropriate local wave steepness spectral parameter. The GF99 dataset allowed investigating for the first time the possible existence of similar threshold behavior in spectral bands above the spectral wave peak region. Figure 1 below shows our breaking probability results for three spectral bands with a relative frequency bandwidth of ±0.3 at the spectral peak frequency and at 1.7 and 2.5 times the spectral peak frequency. These panels indicate a 'universal' behavior for the breaking probability when plotted against the azimuthally-integrated spectral saturation normalized by the spectral peak spreading width. This quantity is proportional to the mean square slope over given relative frequency and directional bands and avoids the issue of sensitivity to the choice of spectral bandwidth.

(ii) *saturation-based spectral dissipation rate source term*

This work has resulted in a proposed new form for the energy dissipation rate due to wave breaking in different parts of the wave spectrum. The basis of the new form is a spectral saturation threshold, as validated in (i) above. The details are given in a paper submitted to the Journal of Physical Oceanography and the model performance in fetch-limited growth against the composite data set of Kahma and Calkoen (1992) is shown in Figure 2.

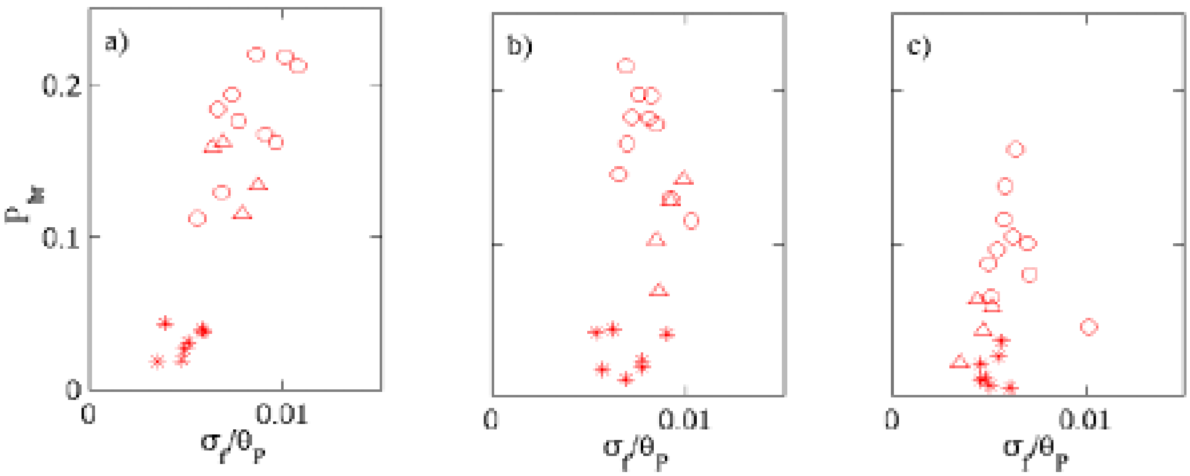

Figure 1. Breaking probability P_{br} showing a 'universal' breaking threshold behavior when plotted as a function of the directionally-normalised spectral saturation $[\sigma_f / \theta_p]$ for three frequency bands relative to the spectral peak (a) $f/f_p=1$ ***(b)*** $f/f_p=1.7$ ***and (c)*** $f/f_p=2.5$***. Each frequency band spans ±30% of the center frequency. Each panel shows the data from three NE Pacific storm sea deployments: (∗) expt III (U_{10}~11-16 ms^{-1}, SWH~4-4.8 m); (○) expt IV (U_{10}~12-20 ms^{-1}, SWH~4-6.6 m) and (Δ) expt V (U_{10}~10-14 ms^{-1}, SWH~3-3.8 m). Here, $\sigma_f = \omega^5 F(\omega)/2g^2$ and θ_p is the spectral spreading width at the peak of the wind sea frequency spectrum*** $F(\omega)$.

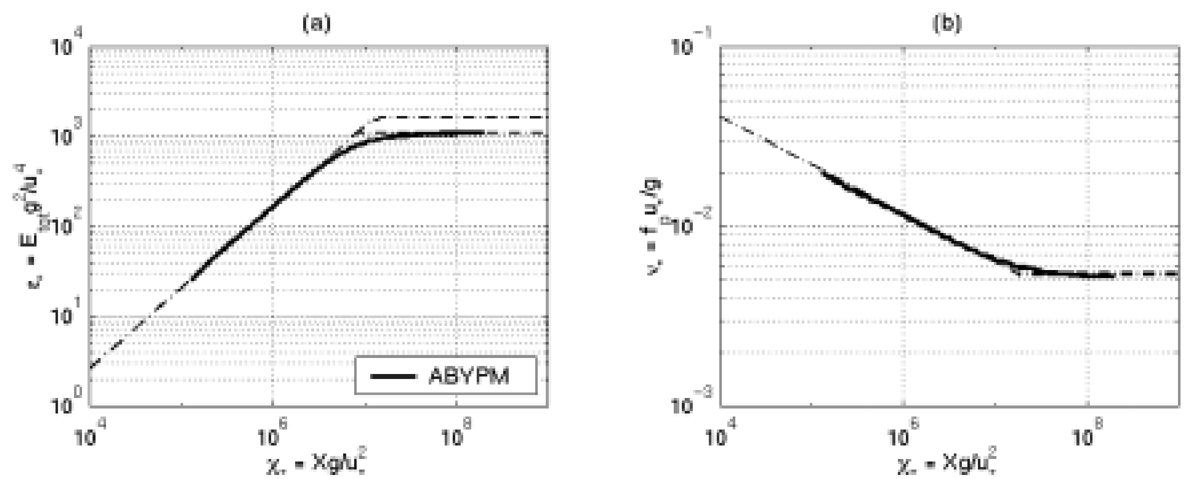

Figure 2. These figures show the close correspondence between model results of our saturation-threshold-based dissipation rate term and the observed fetch-limited evolution of (a) non-dimensional wave energy ε_* (b) nondimensional peak frequency ν_* against nondimensional fetch χ_*, based on friction velocity u_* scaling. The dot-dashed growth curve is the Kahma-Calkoen (1992) empirical data correlation. The horizontal dot-dashed asymptotes represent the Pierson-Moskowitz full development limits for non-dimensional wave energy (panel (a)) and peak frequency (panel (b)). The lower horizontal asymptote in panel (a) is the modified limit of Alves et al. (2001).

(iii) *sea spray/spume droplet production modeling*

As a result of attending the CBLAST PI meeting in Washington, Jan 2001, interactions were initiated with C. Fairall (NOAA, Boulder, CO) and E. Andreas (USACCREL, Hanover, NH) on a refined sea spray/spume parameterization. This has developed into a collaborative venture seeking to develop a new model for spume production based on wave breaking properties rather than wind speed. An initial wave breaking and turbulence model of spume droplet production has been developed.

IMPACT/APPLICATIONS

Enhanced scientific understanding of severe sea state air-sea interfacial processes, particularly wave breaking, will provide more reliable parameterizations of these processes and closely related air-sea fluxes. These improved parameterizations will lead to improved reliability of sea state and marine meteorological forecasts, especially during severe marine wind conditions.

These improvements should also benefit system performance in larger-scale modeling applications, as recently published model sensitivity studies indicate that traditional 'small-scale' phenomena (e.g. wind waves, Langmuir cells, atmospheric roll cells) can impact significantly the modeling of larger-scale ocean and atmospheric circulation.

RELATED PROJECTS

The ONR project *Source Term Balance for Finite Depth Wind Waves* (Young, Banner and Donelan) includes a strong focus on wave breaking observations in constant depth, shallow water environments. The results of the present study for deep water conditions has motivated a similar analysis for the recently gathered Lake George shallow water dataset. This was pursued in FY01 and a paper was published on dominant wave breaking probability in shallow constant depth environments [Babanin et al., 2001]. The impact of wave breaking in enhancing the wind input is being investigated at present.

SUMMARY

This project aims to improve modeling of severe marine weather storm events, including hurricanes. It will include breaking wave effects such as sea spray and water droplets, which are believed to fuel such severe events. To date, our research has resulted in a more robust formula for wave breaking at different scales in terms of the mean steepness of the ocean waves rather than the wind speed. This ONR-sponsored research should lead to more reliable forecasts of severe storms and hurricanes over the ocean, including the likelihood of encountering dangerous large breaking waves.

REFERENCES

Alves, J.H.G.M., Banner, M.L. and Young, I.R. 2001 *Revisiting the asymptotic limits of fully developed seas. Part I: Reanalysis of the Pierson-Moskowitz database.* (submitted to J. Phys. Oceanogr.)

Alves, J.H.G.M. and Banner, M.L. 2001 *Performance of a spectral saturation-based dissipation source term in modeling the fetch-limited evolution of wind-wave* (submitted to J. Phys. Oceanogr.)

Babanin, A.V., Young, I.R and Banner, M.L. 2001 *Breaking probabilities for dominant surface waves on water of finite constant depth*. J. Geophys. Res. Vol. 106, No. C6, 11,659 -11,676.

Banner, M.L., Babanin, A.V. and Young, I.R. 2000 *Breaking probability for dominant waves on the sea surface*. J. Phys. Oceanogr., **30**, 3145-3160.

Banner, M.L., Gemmrich, J.R. and Farmer, D.M. 2001 *Multi-scale measurements of ocean wave breaking probability.* (in preparation for submission to J. Phys. Oceanogr.)

Buckley, B.W. and Leslie, L.M. 1998 *High resolution numerical study of Tropical Cyclone Drena undergoing extra-tropical transition*, Met. and Atmos. Physics, 65, 207-222.

Gemmrich, J.R. and Farmer, D.M. 1999 *Observations of the scale and occurrence of breaking surface waves*. J. Phys. Oceanogr. 29, 2595-2606

Janssen, P. 2000 *ECMWF wave modeling and satellite altimeter wave data.* In 'Satellites, Oceanography and Society', Ed D. Halpern, Elsevier, 367pp.

Kahma, K.K. and Calkoen, 1992 *Reconciling discrepancies in the observed growth of wind-generated waves*. J. Phys. Oceanogr. 22, 1389-1405.

McWilliams, J.C. and Restrepo, J.M. 1999 *The wave-driven ocean circulation.* J. Phys. Oceanogr. 29, 2523-2540.

PUBLICATIONS

Banner, M.L., Babanin, A.V. and Young, I.R. 2000 *Breaking probability for dominant waves on the sea surface*. J. Phys. Oceanogr., **30**, 3145-3160.

Babanin, A.V., Young, I.R and Banner, M.L. 2001 *Breaking probabilities for dominant surface waves on water of finite constant depth*. J. Geophys. Res. Vol. 106 , No. C6 , 11,659 -11,676.

Alves, J.H.G.M., Banner, M.L. and Young, I.R. 2001 *Revisiting the asymptotic limits of fully developed seas. Part I: Reanalysis of the Pierson-Moskowitz database.* (submitted to J. Phys. Oceanogr.)

Alves, J.H.G.M. and Banner, M.L. 2001 Performance of a spectral saturation-based dissipation source term in modeling the fetch-limited evolution of wind-wave (submitted to J. Phys. Oceanogr.).